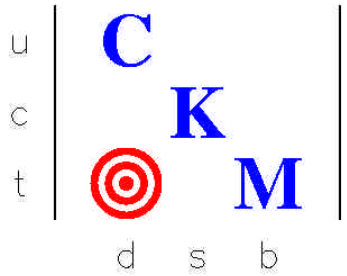
# Future Kaon Physics at Fermilab

## $K^+ \rightarrow \pi^+ \nu\ \bar{\nu}$ and more




***Peter S. Cooper, Fermilab***

***July 30, 2004***

I. Recent history.

II. Physics goals and situation.

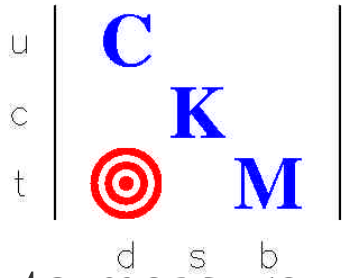
New results from BNL E949

III. A new technique and its challenges

IV. Immediate plans

V. Future Kaon Physics at Fermilab

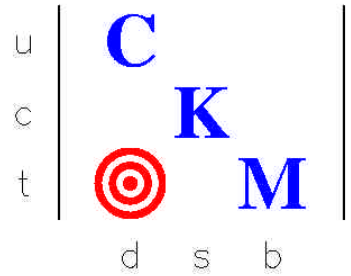
# CKM Status and how to proceed



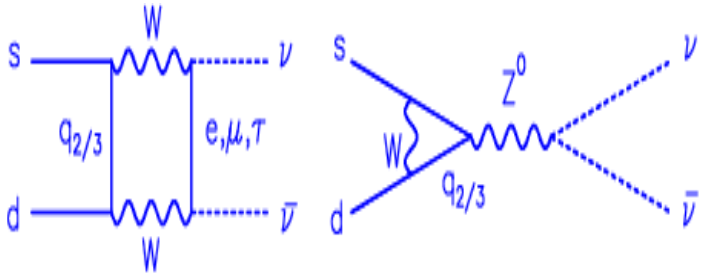

- CKM(E921) at Fermilab is an approved experiment to measure Br[ $K^+ \rightarrow \pi^+ \nu\nu$ ] with 100 signal / <10 background in a high flux separated kaon beam at 22 GeV/c
- **P5** stops **CKM** - Oct 2003

  P5 judged *CKM to be an elegant world class experiment* which *based on present budgetary models should not proceed.*
- Adapt to an unseparated ~45 GeV/c beam in KTeV hall - **P940**
  - Demonstration of μMegas in NA48 ® tracking in 230MHz tractable
  - Other 3 trackers unchanged (2 RICHes + Straws in vacuum)
  - Vetoing photons gets easier ($E_{\pi^0}$ > 1 GeV ® >7 GeV )
  - Accidental backgrounds?

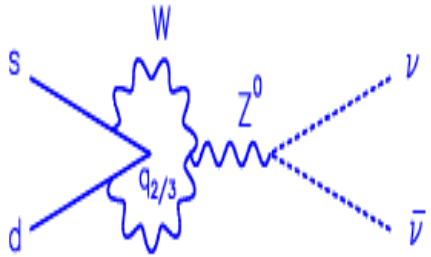
# Primary Physics Goal: Precision Measurement of Br[ $K^+ \to \pi^+ \nu \bar{\nu}$ ]



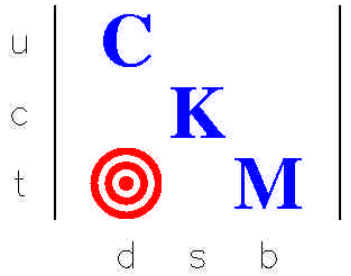

This decay is determined by loop processes to high order in the SM, and hence has a reach for *new physics at the EW scale and beyond*.




The SM rate can be reliably calculated; hence any deviation in the measured rate is a signal for new physics.



# Measuring $|V_{td}|$ with $K^+ \to \pi^+ \nu\bar{\nu}$




- $K^+ \to \pi^+ \nu\ \bar{\nu}$ is the best way to measure $|V_{td}|$ in the Standard Model
  - Structure of $K^+$ controlled by measurement, NO final state interactions.
  - Theoretical uncertainties are small ($m_{charm}$) and robustly estimated. (~8%)
  - Need 100 signal events with <10 background (6%) to match theory error.
- Experimental Challenge
  - Br[ $K^+ \to \pi^+ \nu\ \bar{\nu}$ ] = $(8 \pm 1) \times 10^{-11}$ (Standard Model)
  - 3 clean events seen in BNL787 /949 (Br = $15\ ^{+13}_{-9} \times 10^{-11}$)
- The tyranny of tiny decay rates
  - 100 events / $10^{-10}$ (Br) / 1% (acc) = $10^{14}$ K decays must be studied
  - $10^7$ sec/year $\to$ $10^7$ K decay /sec to see 100 in 1 year
  - Need to control background to $10^{-11}$ of all $K^+$ decays

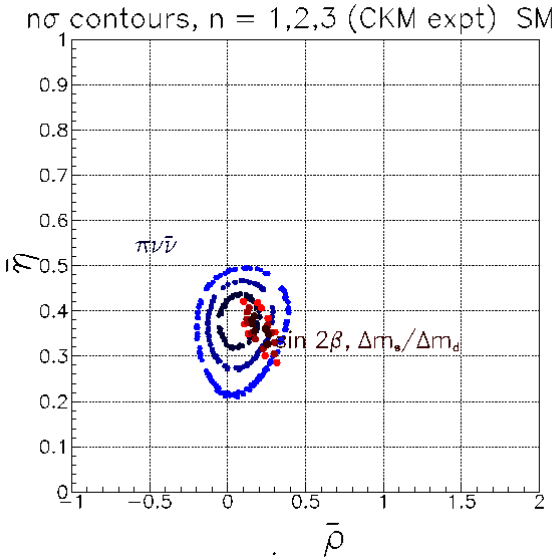
# Challenging the Standard Model of CP Violation

Consider the Quartet of "Golden Mode" measurements:

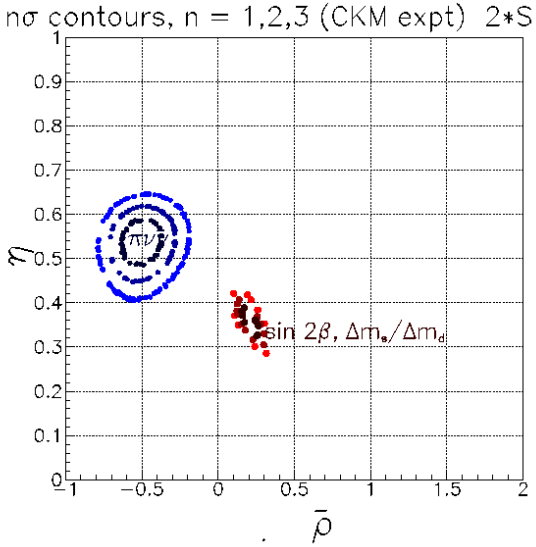
$\sin(2\beta)$, $K^0 \rightarrow \pi^0 \nu\bar{\nu}$, $K^+ \rightarrow \pi^+ \nu\bar{\nu}$,

$\Delta m_d / \Delta m_s$ in $B_d^0$ and $B_s^0$ Decays

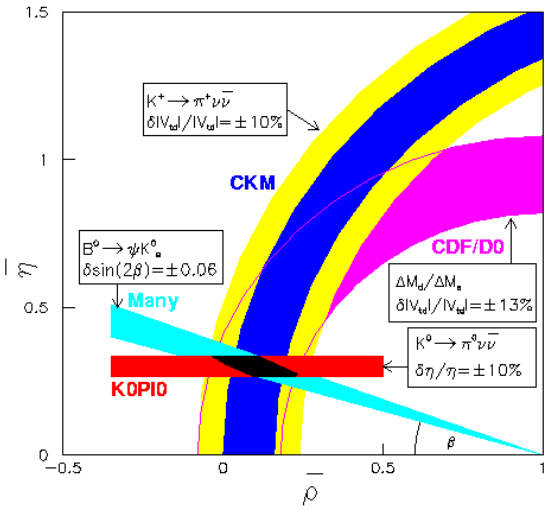
$\Gamma(\pi\nu\nu)$ = SM




$\Gamma(\pi\nu\nu)$ = 2xSM

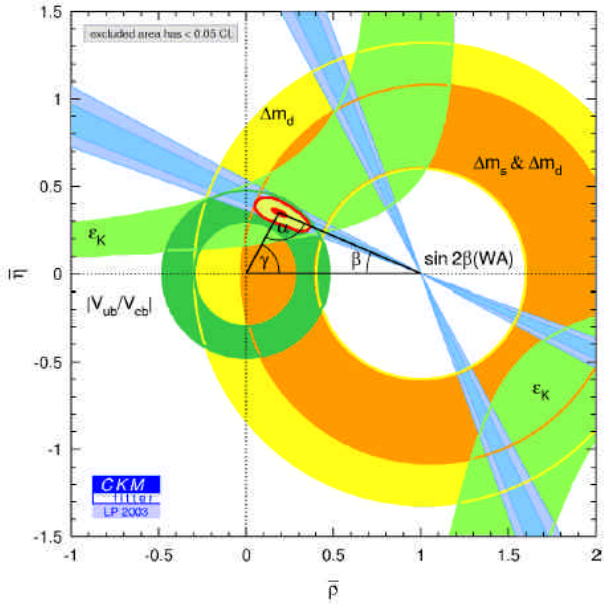



expected sensitivities




CKM Fitter Results, D. Jaffe (BNL).

# Hasn't B physics done it all already?




Who will measure orthogonal to sin 2β?

Bs/Bd mixing CDF /D0 / BTeV /LHCb

But $\xi(\Delta m_s/\Delta m_d) = 1.15\pm0.05^{+0.12}_{-0.00}$

? $1.25\pm0.10$

$B_s$ ? $D_sK$ BTeV / LHCb

$K^+ \to \pi^+ \nu \bar{\nu}$ P940 / NA48-3

•hep-ph/0312259

$B \to \pi\pi$, New Physics in $B \to \pi K$ and Implications for Rare $K$ and $B$ Decays

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Abstract

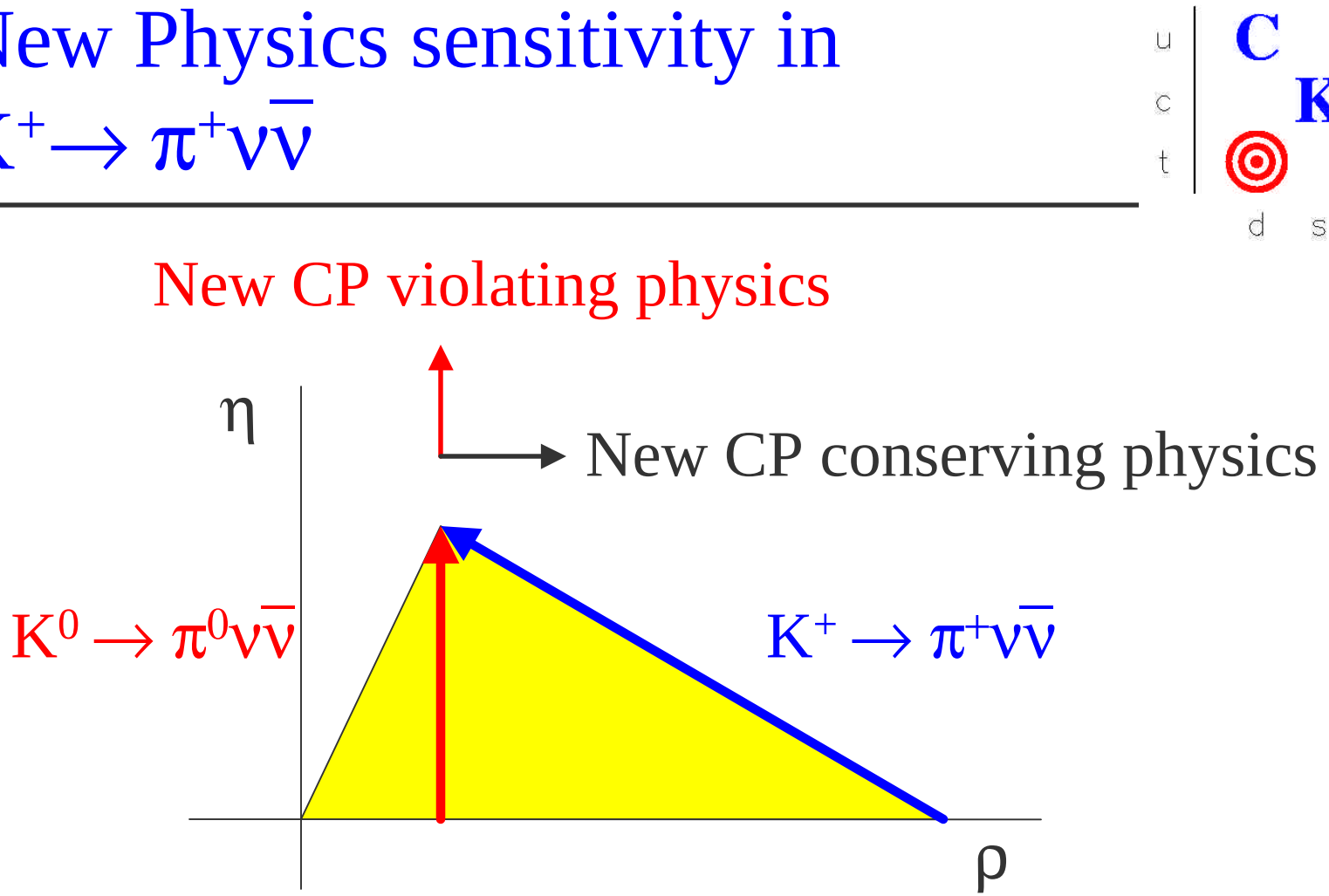
The measured $B \to \pi\pi, \pi K$ branching ratios exhibit puzzling patterns. We point out that the $B \to \pi\pi$ hierarchy can be nicely accommodated in the Standard Model (SM) through non-factorizable hadronic interference effects, whereas the $B \to \pi K$ system may indicate new physics (NP) in the electroweak (EW) penguin sector. Using the $B \to \pi\pi$ data and the SU(3) flavour symmetry, we may fix the hadronic $B \to \pi K$ parameters, which allows us to show that any currently observed feature of the $B \to \pi K$ system can be easily explained through enhanced EW penguins with a large CP-violating NP phase. Restricting ourselves to a specific scenario, where NP enters only through $Z^0$-penguins, we derive links to rare $K$ and $B$ decays, where an enhancement of the $K_L \to \pi^0\nu\bar{\nu}$ rate by one order of magnitude, with $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) > \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$, $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) = \mathcal{O}(10^{-10})$, $(\sin 2\beta)_{\pi K} < 0$, and a large forward-backward CP asymmetry in $B_d \to K^+\pi^-$, are the most spectacular effects. We address also other rare $K$ and $B$ decays, $\varepsilon'/\varepsilon$ and $B_s \to \phi\bar{\nu}\nu$.

•hep-ph/0311353 *Lepton flavor mixing and K® p n `n decays*, Y. Grossman, G. Isidori, H. Murayama

•hep-ph/0112135 *K+® p+ n `n a rising star on the stage of flavor physics*, G. D'Ambrosio, G. Isidori

•many more

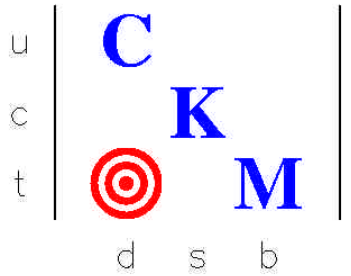
# New Physics sensitivity in $K^+ \to \pi^+ \nu\bar{\nu}$




$K^+ \to \pi^+ \nu\bar{\nu}$ Sensitive to all new physics in s → d transitions

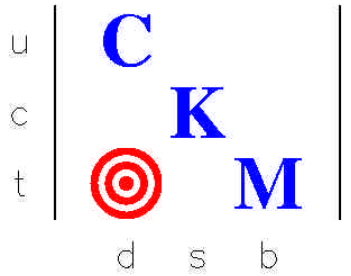
$K^0 \to \pi^0 \nu\bar{\nu}$ Sensitive to only CP violating s → d new physics

# Other Physics Measurements




- $\pi^+$ decay physics
  - $\Gamma[\pi^+ \to e^+\nu(\gamma)]/\ \Gamma[\pi^+ \to \mu^+\nu(\gamma)]$ is calculated to 0.05% in the SM
  - Helicity suppresses the dominant V-A and IB amplitudes
  - $\pi^+ \to e^+\nu\gamma$ Dalitz plot – access to non V-A terms in hadronic weak current
  - An excellent place to search for models like leptoquarks, multiple Higg, etc.
- Other $K^+$ decay physics
  - All the other K decays studies from the CKM proposal remain
    - $K_{e3}$, $K_{e4}$, $K_{\mu 3}$, $K_{\mu 4}$, $K^+ \to \pi^+ e^+ e^-$ , $K^+ \to \pi^+ \mu^+ \mu^-$
    - Lepton flavor violation - $K^+ \to \pi^- \mu^+ \mu^+$, etc.
    - T odd correlations in $K^+ \to \pi^+ l^+ \nu\gamma$
  - $\Gamma[K^+ \to e^+\nu(\gamma)]/\ \Gamma[K^+ \to \mu^+\nu(\gamma)]$, $K^+ \to e^+\nu\gamma$ in parallel with pion decays

# Changes in the physics situation



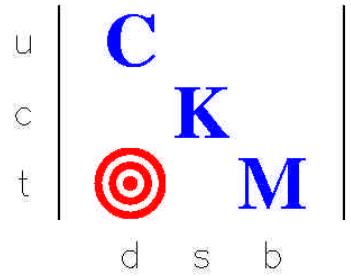

## What's changed since the CKM approval in 2001?

- Another $K^+ \to \pi^+ \nu \bar{\nu}$ event from BNL E949 (see below).
- $B_s$ mixing isn't going to be measured at the SM level (17 $ps^{-1}$) soon.
- Some unusual CP violation results are emerging at Belle
  - e.g. $B^0 \to \phi K_S^0$ asymmetries disagrees with $\psi K_S^0$ (& $K^+K^-K_S^0$, $\eta' K_S^0$)
- Lack of 1st row unitarity (~2.5σ) and new measurements of $V_{us}$- resolved(?)
- There is experimental evidence for non V-A terms in the pion hadronic weak current in $\pi^+ \to e^+ \nu \gamma$
  - 5σ claim by PiBeta for tensor form-factor $F_T/F_V = -0.061 \pm 0.011$

    hep-ex/0311013, hep-ex/0312029
  - ISTRA at IHEP also reported a non-zero tensor form-factor.

    Phys.Lett.**B243** (1990)308, hep-ph/0307166

# New Results from BNL 949



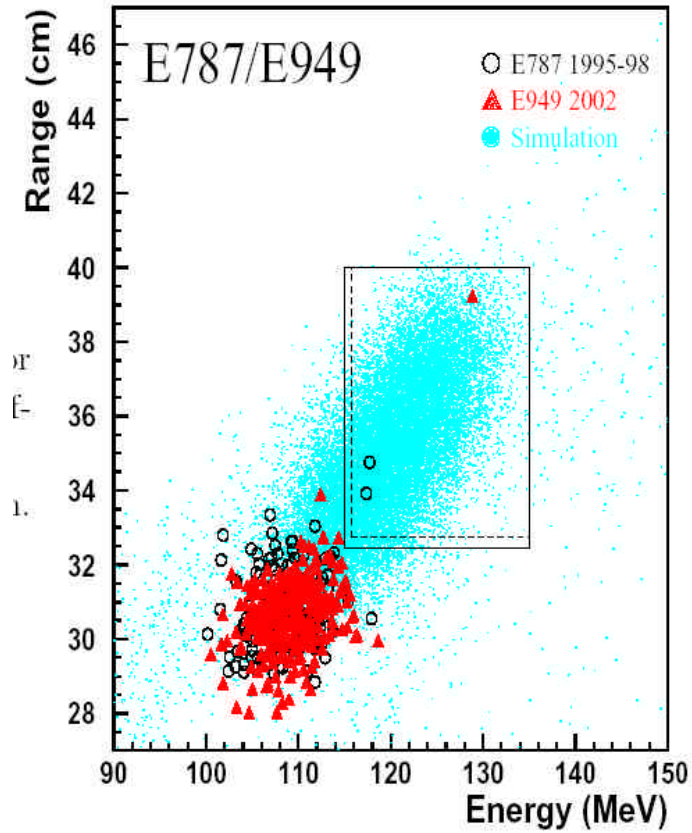

- $K^+$ Decay at rest experiment with the BNL – AGS% "proton blowtorch".
- Third $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ event.
- S/N ~ 1 :this event could be either signal or background
- Combined E787 / E949 results

$$Br(\pi^+ \nu \bar{\nu}) = 1.5\ ^{+1.3}_{-0.9}) \times 10^{-10}$$

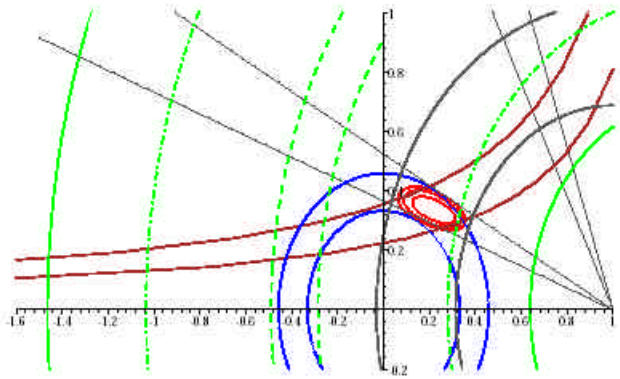
$$> 0.42 \text{ x' } 10^{-10} \text{ 90\% CL}$$

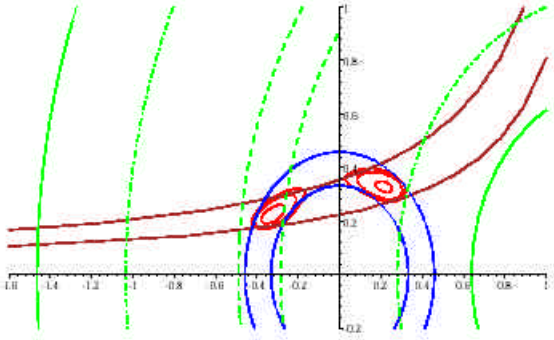
$$< 3.22 \times 10^{-10} \text{ 90\% CL}$$

- 10-20% of approved data. Further running unlikely.



# $B(K^+ \to \pi^+ \nu\nu)$ and the Unitarity Triangle



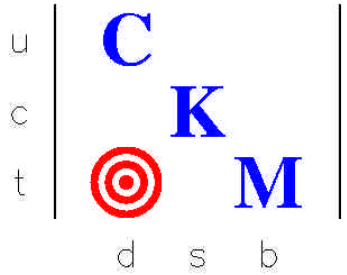


- Green lines show $B(K^+ \to \pi^+ \nu\nu)$ with theoretical uncertainty.
  Central value (dashed), 68% (dot-dashed), 90% (solid)'
- Red ovals show 68%, 90%, 95% contours from other measurements
  $V_{ub}$, $\varepsilon_K$, sin (2β), $\Delta m_d$, $\Delta m_d/\Delta m_s$
- Right figure doesn't include measurements dependent on $B_d$ mixing (blue) '

Figure provided by Gino Isidori

How does this compare with recent CDF measurement of $\Delta\Gamma_s$ in $B_s$ decay?

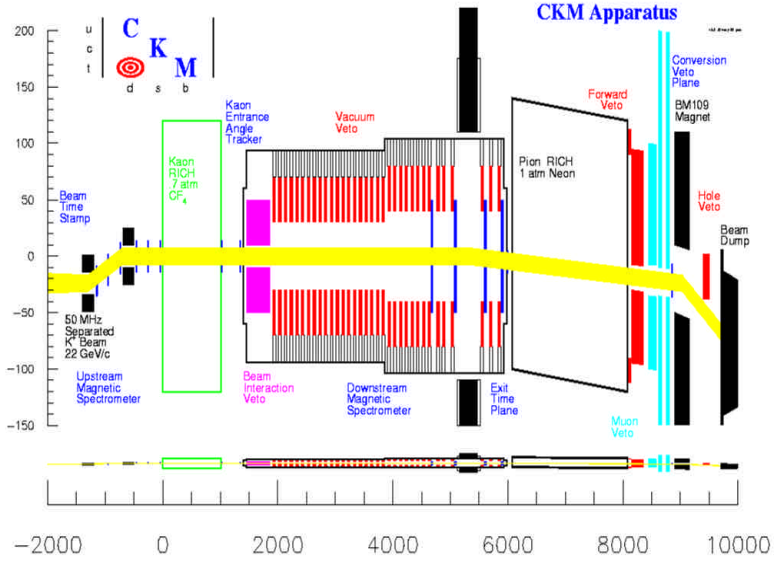
# Experimental Technique

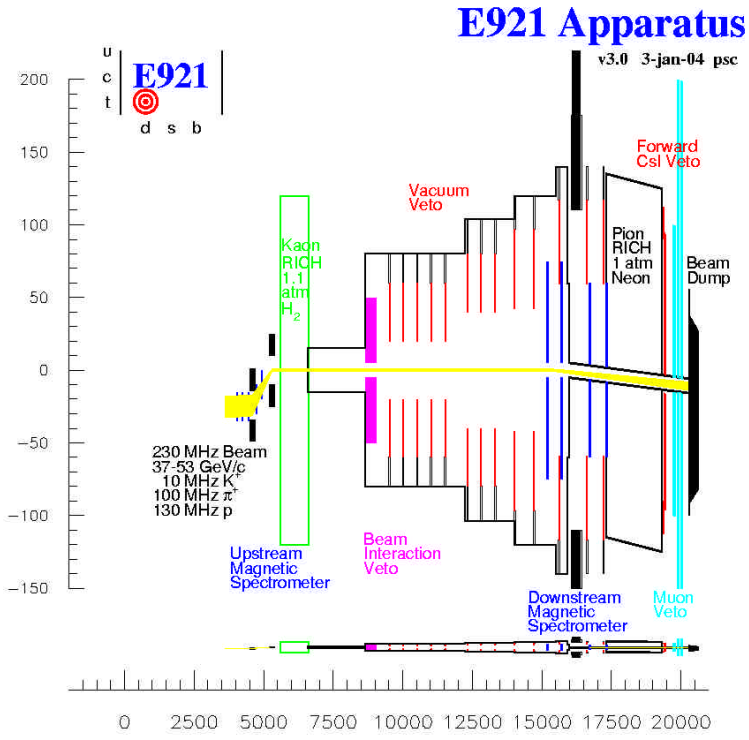



- High Flux Un-separated 37-53 GeV/c Beam - 4% $K^+$
  - Proton / $\pi^+$ : 120 / 100, 230 MHz total, 1x1 $cm^2$, 0.1x0.1 $mRad^2$
  - 10 MHz $K^+$, 1.7 MHz decay in the acceptance.
  - 5 x$10^{12}$ 120 GeV proton /sec in slow spill from the Main Injector to produce the required $K^+$ beam (17% of design intensity)
  - Debunched proton beam required (~10% 53MHz ripple ok).
- Apparatus
  - Decay in flight spectrometer with both velocity (RICH) and momentum (magnetic) spectrometer both both $K^+$ and $\pi^+$.
  - Significant requirements on photon vetoes
  - All detector technologies used are well established
  - **Redundancy** is critical to measure all backgrounds
  - Exploit signal regions on both sides of $K^+ \rightarrow \pi^+\pi^0$.

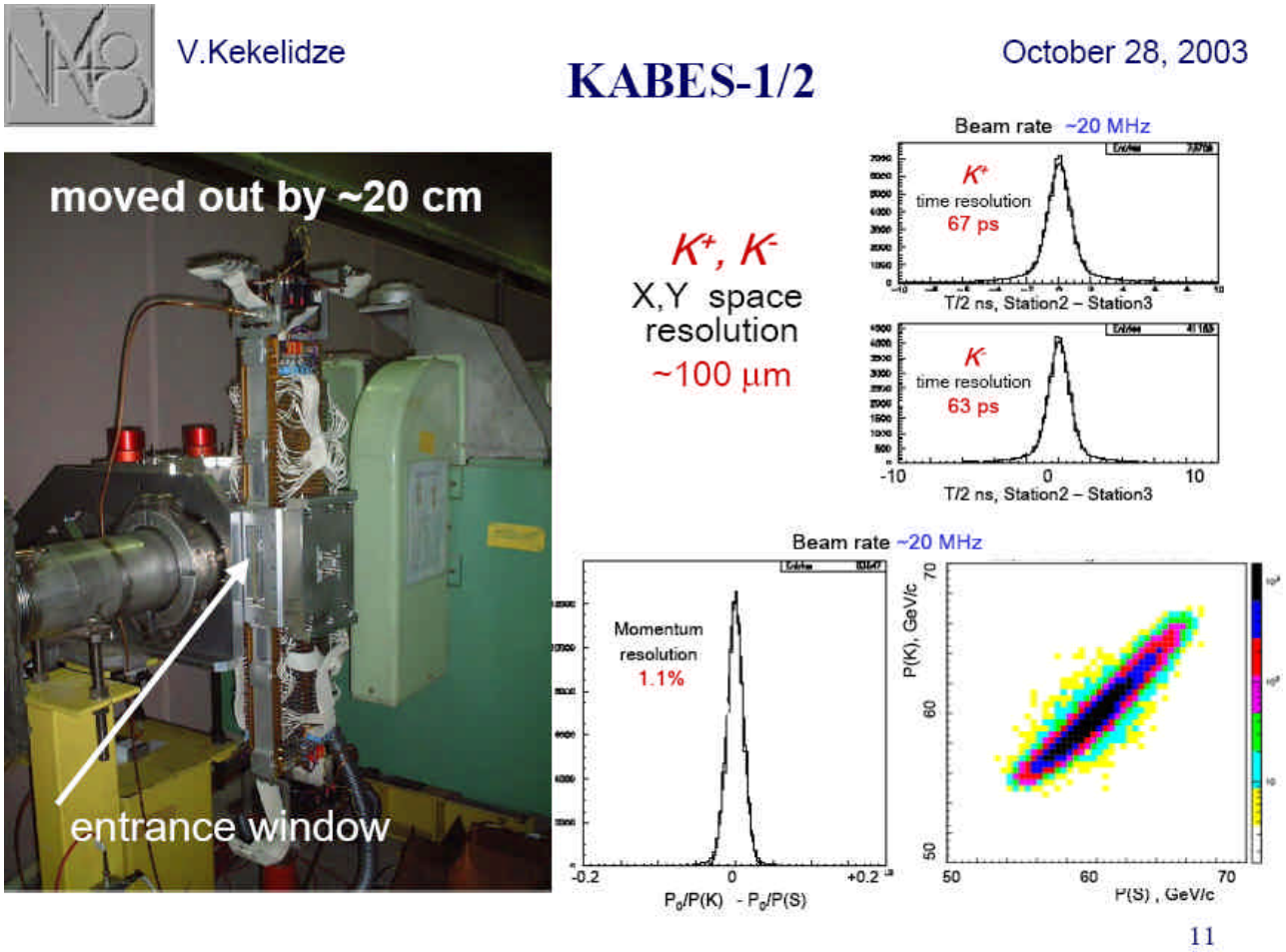
# Apparatus

- Decay in flight
- Redundant high rate detectors and veto systems.
- separated K+ beam at 22 GeV/c. Un-separated + beam at 37-53 GeV



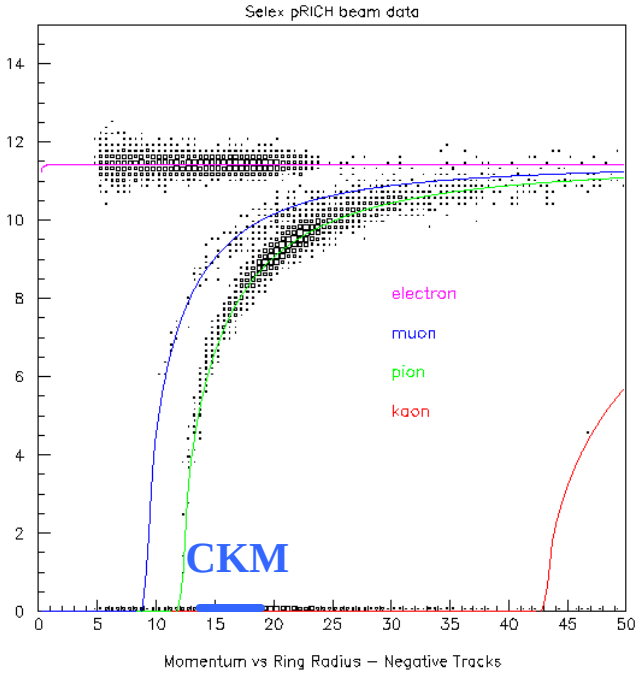



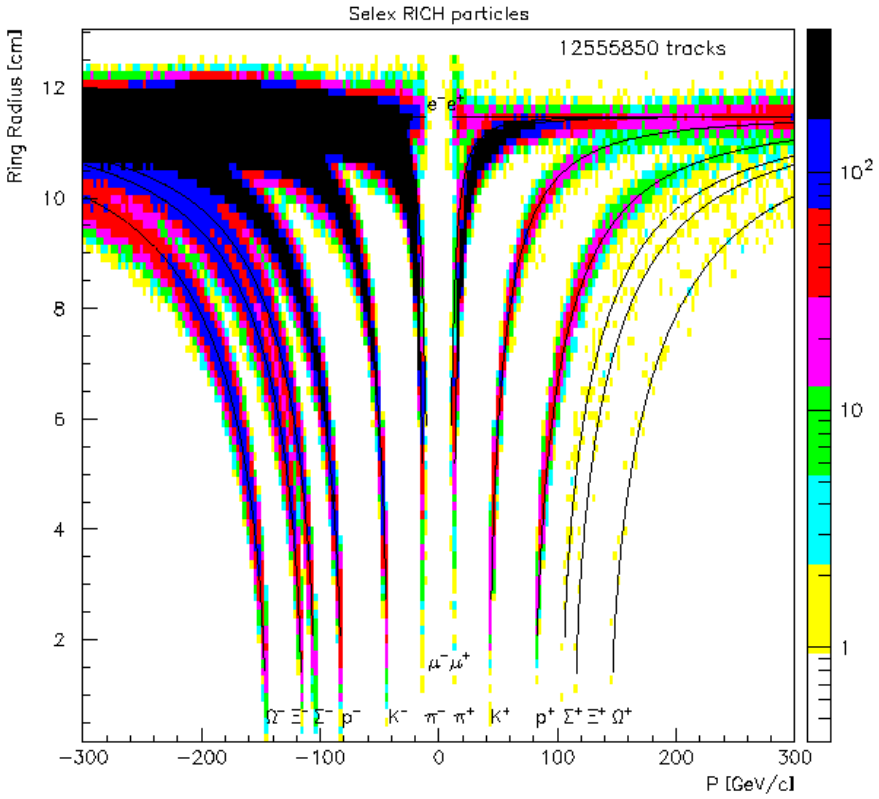
# NA48 KABES data



# Ring Imaging Cherenkov Counters

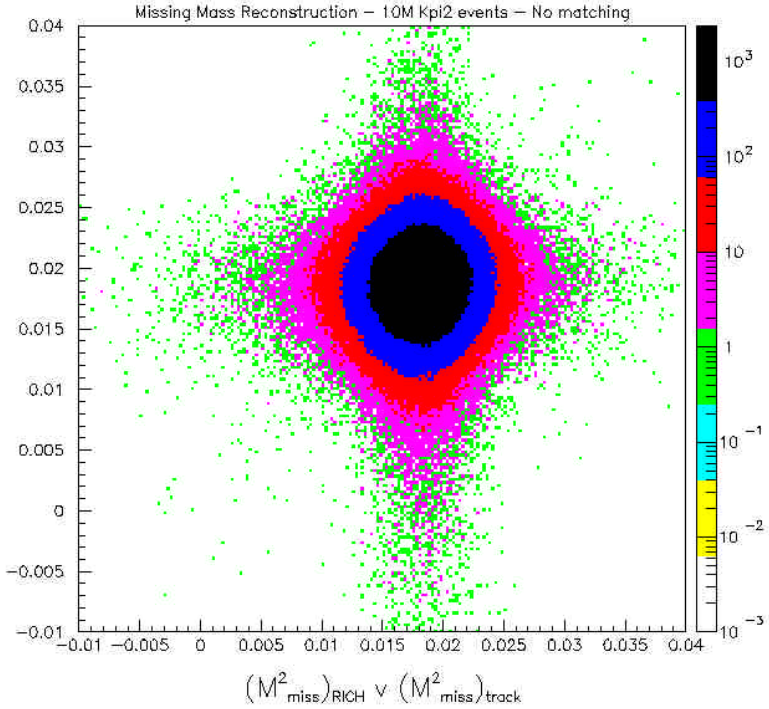
- High rate high resolution
- Matched to momentum resolution
- Based on successful Selex RICH
- Photo-detectors are individual PMTs



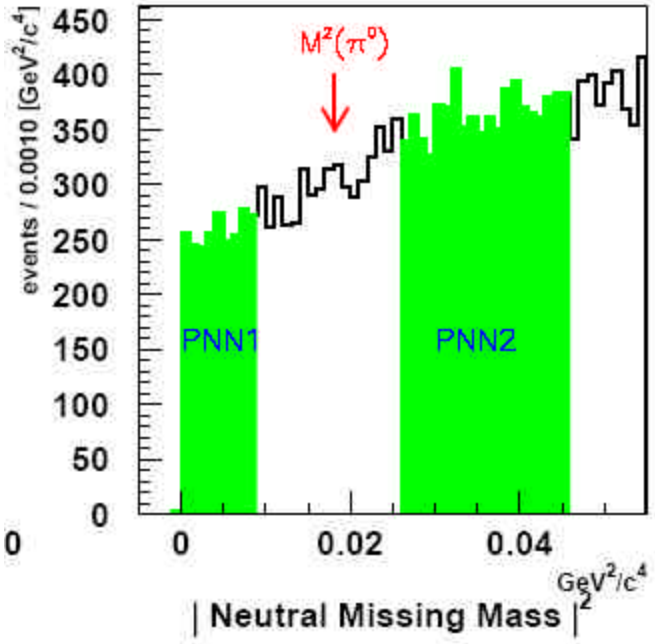
# Simulated Spectrometer Performance

- Missing mass resolution for $M^2_{\pi^0}$ from $K^+ \rightarrow \pi^+ \pi^0$
- Matched resolution from momentum and velocity spectrometers
- Low non-Gaussian tails
- Uncorrelated measurements
  - Backgrounds from Mis-measurements to be studied and quantified from the data
- Study needs to be redone for P940



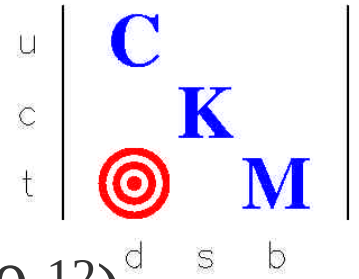
# Acceptance

- Acceptance was re-evaluated. Decay fraction increased 13% → 16.5%
- PNN2 acceptance limited to 1.4x PNN1 pending more serious background studies
- Nearly identical sensitivity as CKM for same 120 GeV beam incident.



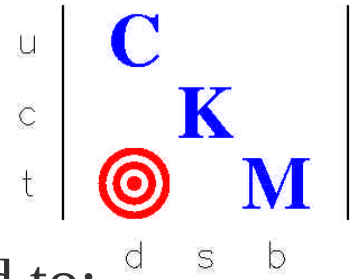

| parameter | CKM | E921 |
|---|---|---|
| $K^+ flux[MHz]$ | 30 | 10 |
| beam-sec/year | $0.75 \times 10^7$ | $0.75 \times 10^7$ |
| years of data | 2 | 2 |
| sensitive K decays | $5.8 \times 10^{13}$ | $2.5 \times 10^{13}$ |
| nominal Branching ratio | $1 \times 10^{-10}$ | $1 \times 10^{-10}$ |
| taxes (other losses) | $-15\%$ | $-15\%$ |
| PNN1 (s+b) | $95+ \leq 10$ | $44+ \leq 4$ |
| PNN2 | $(130+ \leq 40)$ | $62+ \leq 20$ |
| total | $95+ \leq 10$ | $106+ \leq 24$ |
| Br precision | $< 11\%$ | $< 12\%$ |

# Backgrounds Remaining



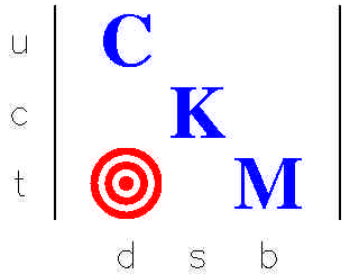

| Background Source | Effective BR ($\times 10^{-12}$) CKM | P940 |
|---|---|---|
| • $K^+ \rightarrow \mu^+ \nu_\mu$ | < 0.04 | - |
| • $K^+ \rightarrow \pi^+ \pi^0$ | 3.7 | ~5 |
| • $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ | < 0.09 | - |
| • $K^+ A \rightarrow X K^0_L \rightarrow \pi^+ e^- \nu$ | < 0.14 | TBD |
| • $K^+ A \rightarrow \pi^+ X$ (trackers) | < 4.0 | TBD |
| • $K^+ A \rightarrow \pi^+ X$ (gas) | < 2.1 | TBD |
| • Accidentals ($K^+$ + beam track) | - | TBD |
| • Accidentals (2 $K^+$) | 0.51 | 0.17 |
| • TOTAL | <10.6 | TBD |

# Our plan




- We are in the middle of this redesign now – we need to:
  - Complete the unseparated beamline design for NM2
  - Assess KABES feasibility in a 230 MHz beam
  - Re-evaluate backgrounds from Kaon interaction in detectors
  - Estimate backgrounds from non-kaon interaction accidentals
  - Evaluate PNN2 cuts, acceptance and backgrounds
  - Re-assess losses from deadtime, reconstruction, …
- Our Plan
  - Complete the list above
  - Have external technical review of the redesign (a-la CKM)
  - Return to Fermilab and the PAC with a vetted re-design
  - Time scale of months

# Future Kaon Physics at Fermilab




- Fermilab is planning a Proton Driver to increase fluxes by ~10x
  - Both an 8 GeV SCRF proton Linac and an 8/16 GeV high flux conventional synchrotron are under consideration.
  - Physics goals include sensitivity neutrino experiments, …
  - Time frame is the next decade (~2015)
- High Sensitivity Kaon physics is a natural for this machine - **but**
  - The Main Injector was sold on the same promise in ~1989
  - Save the KTeV 1999 run no kaon physics will be done in the first decade of main-injector operation
- If Fermilab and US-HEP aren't interested in a kaon physics program for today, discussing one in a decade is fatuous.
- CERN is considering the same experiment as NA48-3